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THE SOLAR CONSTANT OF RADIATION[1]

WE live in a world warmed by the sun. While it is not to be expected that everybody will devote himself to the measurement of solar radiation, yet it is not surprising that many have concerned themselves with measuring the quantity on which all lives depend. So far as I am aware, this subject was not pursued by the ancients to such a point as to obtain measurements worth much present consideration. This is a great pity, for thus we lack proof whether the sun's radiation has changed progressively. Beginning about a century ago investigations of solar radiation were pursued with great assiduity by various observers. The need was almost immediately perceived of reducing the observations to represent conditions outside the earth's atmosphere, as, for example, on the moon, so as to be independent of the haze and water vapor and even of the gaseous constituents of the air. It is required to know the measure of solar radiation in free space as an index of the condition of the sun, quite apart from its influence on terrestrial affairs, but secondly it is of great importance and interest to apply this knowledge to promote meteorological inquiries.

Sir John Herschel, who was a pioneer in solar radiation work, proposed to express solar radiation in terms of a unit which he called the actine, which is based on the melting of ice. But by general consent the gram calorie has been adopted as the unit of measurement, and we say that the

[1] Address delivered before the Philosophical Society of Washington, January 3, 1914, as retiring president.

"solar constant of radiation" is the number of calories per square centimeter per minute which would be produced by the complete absorption of the solar radiation in free space at the earth's mean solar distance.

Preparatory researches of great interest were made in the eighteenth century by Bouguer, Lambert, DeSaussure and Leslie. Determinations of the solar constant of radiation, however, may be said to have begun about eighty years ago with the investigations of Sir John Herschel, Principal Forbes and Pouillet. The problem comprises two parts: first, to measure the intensity of the solar radiation at the earth's surface; second, to estimate the loss it has suffered in passing through the atmosphere. It will be convenient to consider the atmospheric influence briefly before taking up the methods of measuring the solar radiation, and then to return to a more thorough discussion of the atmospheric transmission.

ATMOSPHERIC TRANSMISSION

The determination of the transmission of the atmosphere rests primarily upon the hypothesis of Bouguer, first put forward in the year 1729 and elaborated in Bouguer's posthumous work published in the year 1760. The late Dr. Langley has placed this matter in so very clear a light in his paper on the "Amount of the Atmospheric Absorption"[2] that I can not do better than to quote from his statement.

If a beam of sunlight enters through a crevice in a dark room the light is partly interrupted by the particles of dust or mist in the air, the apartment is visibly illuminated by the light laterally reflected or diffused from them, and the direct beam, having lost something by this process, is not so bright after it has crossed the room, as before. In common language, the direct light, to an observer in the path of the beam, has been partly "absorbed," and the problem is, to determine in what degree. If a certain portion of the light (suppose one fifth) were thus scattered, the beam after it crossed the room would be but four-fifths as bright as when it entered it; and, if we were to trace the now diminished beam through a second apartment altogether like the other, it seems at first reasonable to suppose that the same proportion (*i. e.*, four fifths of the remainder) would be transmitted there also, and that the light would be the same kind of light as before, and only diminished in amount (in the proportion $4/5 \times 4/5$). The assumption originally made by Bouguer and followed by Herschel and Pouillet, was that it was in this manner that our solar heat was absorbed by our atmosphere, and that by assuming such a simple progression the original heat could be calculated.

If A_0 be the intensity of the original beam before entering the transparent medium whose transmission is to be investigated, then after the passage through the first stratum of unit thickness let us suppose a fraction of the original represented by p has passed through, so that what was A_0 becomes A_0p. Then since a second stratum identical with the first in constitution and thickness must, according to Bouguer's assumption, have an identical effect, the ray which was A_0 will emerge from the second stratum A_0p^2, and so on. The fraction p transmitted by the unit of thickness is the common ratio of a geometric progression, so that after passing through a thickness m of the medium, the intensity of the light which was formerly A_0 will become A_0p^m.

As the height to which the atmosphere extends in appreciable density is very small compared with the radius of the earth, the thickness of the layer traversed by a solar beam of a zenith distance not exceeding 70° is approximately proportional to the secant of the zenith distance of the sun at the time of observation. If we regard unit thickness as that corresponding to barometric pressure of 760

[2] *American Journal of Science*, Third Series, Vol. 28, September, 1884.

millimeters of mercury, then p in our formula corresponds to the vertical transmission coefficient of the atmosphere above sea level, and for any station where the barometric pressure is B the intensity of the ray from the sun as it reaches the earth's surface, which we call A, may be expressed by the formula

$$A = A_0 p^{(B/760)\sec z}.$$

Some writers have preferred to use the formula as a formula of "absorption" rather than of transmission. In that way the expression reduces to a somewhat different form, but its fundamental principles are the same. The investigations of Herschel, Forbes, Pouillet and others up to the time of Langley had reference to this exponential formula based upon the hypothesis of Bouguer, which was to the effect that successive equal layers of transparent material transmit equal fractions of the incident ray.

A convenient method of applying the atmospheric transmission formula is to take logarithms of both members of the equation so as to reduce the expression to the form of the equation of a straight line. Thus

$$\log A = \frac{B}{760} \sec z \log p + \log A_0.$$

By this equation the intersept of the best straight line on the axis of ordinates is the logarithm of the intensity of solar radiation outside the atmosphere, and the inclination of the line to the horizontal is the logarithm of the atmospheric transmission for vertical rays.

The reader must bear in mind that the simple expression thus far obtained is given only in illustration of the work of the earlier investigators, and it must be hedged about with certain conditions and limitations in order to apply it, as we shall see later, to the determination of the solar constant of radiation by the most approved methods.

INSTRUMENTS

Herschel's Actinometer.—This instrument consists of a thermometer with a large cylindric bulb, containing a deep blue fluid (the ammoniacal sulphate of copper) and enclosed in a wooden case blackened interiorly and covered with a piece of thick plate glass. The thermometer has a very large bulb, and it is adjusted in volume by means of a screw, so as to regulate the position of the column of liquid on the thermometer scale. Herschel introduced what is termed the dynamical method of observing the solar radiation, for he obtained not the total rise of temperature of the instrument when long exposed to the sun, but its initial rate of rise, corrected for the cooling or warming of the thermometer due to external conditions when the sun is shaded. The determination of the cooling correction is done by observing the rise or fall of the temperature for a certain time interval before exposing to the sun, and again determining the rise or fall after such exposure to the sun is completed. The mean rate of warming or cooling, due to the surroundings, is applied as a correction to the rate of warming due to the exposure to the solar radiation.

Pouillet's Pyrheliometer.—A flat metal box, blackened on the front, and filled with water, had a thermometer inserted at the rear, extending away from the direction of the sun. The instrument, like that of Herschel, was exposed to the influence of the surroundings while shaded for a certain interval of time the shade was then removed for a similar interval so as to allow the solar radiation to fall upon the blackened box, after which the instrument was again shaded. In practise it was found that the water within the box could not be well enough stirred in order to allow the average

temperature of the water to be well ascertained. The instrument was greatly improved by Tyndall, who substituted mercury for water, and, in order to contain the mercury, used iron in the making of the box.

Crova Alcohol Actinometer.—A large spherical bulb thermometer containing alcohol is enclosed in a nickel-plated metal chamber with a vestibule for the entrance of the rays. The stem of the thermometer runs back, directly away from the sun, and is enclosed in a nickel-plated tube with a side opening for reading the thermometer. A short mercury thread is introduced in the alcohol column at a suitable point for observing. The method of observing is the same as that adopted by Herschel and by Pouillet.

Violle Actinometer.—A large spherical double-walled enclosure filled with water is kept at a known constant temperature. A spherical blackened-bulb thermometer lies at the center of the enclosure, and the sunlight is introduced to it through a suitable vestibule in the double-walled chamber. Violle's method of reading was static, as opposed to the dynamic methods we have just considered. He observed the total rise of the thermometer and its fall after the cutting off of the sun rays, noting the position of the column at fixed intervals after exposure and after closure. The theory of the instrument as developed by Violle is simple and elegant. As a standard the instrument is open to the objection that the water equivalent of the bulb of the thermometer is very small, and difficult to measure, and that several corrections rather difficult of determination should be applied. It was used by Dr. Langley in his expedition to Mount Whitney in 1881.

Ångström Electrical Compensation Pyrheliometer.—This instrument has had the most extensive adoption in recent years of any form of instrument for measuring the solar radiation. It was invented about the year 1895. Two metal strips exactly similar to one another, and blackened upon the front, are exposed alternately to heating by the sun. Arrangement is provided for passing an electrical current through the strip which is not at the moment being heated by the sun. Thermo-elements fastened to the back of each strip indicate when the temperature of the exposed strip is equal to that of the strip which is electrically heated. Under these circumstances it is assumed that the energy of the electric current is equal to the energy received from the sun. About 160 copies of this electrical compensation pyrheliometer have been sent out from Upsala to different parts of the world.

Several other kinds of pyrheliometers have been used in recent years, among them two forms which have been devised by the writer. We shall have occasion to speak of these later.

EARLY OBSERVATIONS

Forbes observed with the Herschel actinometer in the year 1832 at Brientz and the Faulhorn. He showed that the transmissibility of sun rays continually increases as the length of path of the ray in air increases. Forbes rightly attributed this to the non-homogeneity of the solar radiation, and the inequality of transmission of the different component parts of it. Under such circumstances Bouguer's formula of course can not apply. Forbes concluded that equal barometric columns of air give equal transmission, whether taken from the high or low station. In this he was wrong. He formed an empirical curve to represent all his observations at both stations, employing air masses as abscissæ and actinometer readings as ordinates. Instead of extrapolating this curve directly to air

mass zero he preferred to find its tangents and thus derive the subsidiary curve of tangents from which he derived a formula for extrapolating his observations. In this way he obtained results corresponding to the value 2.85 calories per square centimeter per minute for the solar constant. Thus Forbes cut loose entirely from Bouguer's exponential formula of atmospheric transmission.

Pouillet observed in the years 1837 and 1838 at Paris. His work was published before that of Forbes, although made later. He found transmission coefficients by means of Bouguer's formula. He apparently did not investigate the defects of this formula as thoroughly as Forbes did. His result for the solar constant of radiation is 1.7633 calories per square centimeter per minute. This value, on account of the nonhomogeneity of the solar rays, is necessarily too low.

Quetelet observed with a Robinson actinometer similar in form to Herschel's, at Brussels from the year 1843 to 1853. These experiments might well repay a critical examination now, not for their value in determining the absolute measure of the solar constant of radiation, but in connection with the variation of the average intensity of the solar radiation from year to year as influenced by volcanic eruptions.

Desains employed a thermopile, and compared the transmissibility of the rays of the sun through a water cell at different stations. He found the transmissibility of solar rays through the water cell always increased by a long preliminary course through moist air. This result is essentially the same as that of Forbes, although obtained in a different manner.

Violle observed at many different stations, including Mont Blanc. His instrument apparently read much too high, as noticed by Langley in the report of the Mount Whitney expedition. He used a somewhat complicated empirical formula of extrapolation, as he was fully cognizant of the defect of Bouguer's formula, as indicated by Forbes. He obtained the following values:

	Outside Atmosphere	Mt. Blanc	Grand-Mulet	Bossons	Paris
Altitude	—	4,810	3,050	1,200	60
Barometer	0	430	533	661	758
Calories	2.54	239	2.26	2.02	1.74

These values should be reduced about one fourth to make them comparable with observations made in recent years at high elevations by many observers. In such a case the value outside the atmosphere would become about 1.9 calories per sq. cm. per minute.

Crova made many observations at Mont-Pellier with his alcohol actinometer standardized against the Tyndall pyrheliometer. He made some attempts to extrapolate his observations to the limit of the atmosphere, but these, like other solar constant values obtained by pyrheliometry alone, are not definitive. Great value, however, attaches to the long series of direct observations continued from the year 1883 to 1900 at Mont-Pellier. These show plainly the influence of the volcano Krakatau and others.

K. Ångström observed with the electrical compensation pyrheliometer at several stations at different altitudes on the island of Teneriffe in the years 1895 and 1896. Some of his measurements were made at the altitude of 3,700 meters, and give direct readings of solar radiation as high as 1.63 calories per square centimeter per minute. Angström declined to determine from these a value of the solar constant of radiation, recognizing that this demanded observations of the solar spectrum as well as pyrheliometric work. In later years he

prepared spectro-bolometric apparatus for this purpose, and made many solar constant measurements therewith at Upsala. These measurements are still being continued there by his successors. It is hoped that this long and interesting series will soon be published.

Passing from this work of Ångström, which belongs in a later period, and omitting mention of valuable pyrheliometric observations by numerous observers in Italy, Switzerland and Russia, which I regret that space forbids me here to discuss, attention must now be directed to the work of Langley, which marked an epoch in this kind of investigation.

LANGLEY'S OBSERVATIONS

Prior to Langley's observations there had been numerous attempts to determine the solar constant, which are well summed up in the excellent little book of Radau, entitled "Actinometrie." It is shown that nearly all observers were in comparative agreement, so far as their actual observations go, and if the transmission of radiation by the atmosphere be estimated by the simple formula

$$A = A_0 p^{B/760 \sec z},$$

which was employed by Pouillet and many others, the value of the solar constant would be found in the neighborhood of 1.75 calories.

But Forbes, Desains, Violle, Crova and others showed convincingly that this equation does not accurately express the diminution of radiation attending the decline of the sun from zenith to horizon, or the descent of the observer from a high altitude to a lower one. Accordingly several empirical formulæ of more complexity were proposed, which, owing to their more numerous constants, could be made to fit the observed variation of the total intensity of radiation under different conditions more closely. By the aid of such empirical formulæ higher values of the solar constant have been obtained. Some of these in our own time have gone as high as 4 calories. Radau however says:

> It is clear that the intensity of the solar radiation outside the atmosphere can not be certainly obtained from experiments which have been made [prior to 1871], for the result depends essentially on the manner of calculation.

This conclusion is still applicable to pyrheliometer measurements not supported by spectrum observations.

The tendency toward high values of the solar constant was powerfully stimulated by the publication of the report of the Mount Whitney expedition by Langley in 1884. As Forbes and Radau had stated, so Langley emphasized and acted upon the fact that the formula

$$A = A_0 p^{B/760 \sec z}$$

applies only to a homogeneous bundle of rays in a pure atmosphere; and the intensity of solar radiation outside the atmosphere can only be exactly determined when the atmospheric transmission coefficients of the rays of all wave-lengths, which go to make up the complex beam of the sun, are separately determined and allowed for. Langley was the first to determine and apply atmospheric transmission coefficients for numerous rays of different wave-lengths in the solar spectrum. For this purpose he invented the bolometer, a delicate electrical thermometer, and observed with it the variation of the intensity of each ray of the spectrum from low sun to high. He found it impracticable to determine the transmission coefficients in the water vapor bands of the infra-red, but assuming that there were no water vapor bands in the solar spectrum outside our atmosphere, he avoided this difficulty by smoothing the spectrum energy curve, which he computed from his bolometric observations to repre-

sent the distribution of solar radiation outside the atmosphere, so as to leave no water vapor bands in it at all. Had Langley stopped with these steps accomplished, he would have left us, as the result of the Mount Whitney expedition, 2.060 calories, the mean value as determined by high and low sun observations at Lone Pine, or 2.220 calories, the mean value similarly determined from observations at Mountain Camp. But, by the train of reasoning given on pages 142–144 of his report, he convinced himself that the exponential formula does not hold for the earth's atmosphere, even for a strictly homogeneous ray. He therefore altered his results by two different procedures, one of which he states was of a kind to give too low a value of the solar constant, and the other too high. By this means he obtained the values 2.630 and 3.505. The mean of these, 3.068, or in round numbers 3.0 calories per sq. cm. per min., he adopted as the solar constant. But in fact, both procedures were calculated to give too high results, and the most probable results of Langley's observations lies below either of them, and is in fact 2.22, or 2.06 calories, according as the work at Lone Pine or Mountain Camp is regarded as the better. In order to recognize this, it is necessary to examine the argument which led him to doubt the accuracy of the exponential formula, as applied to the transmission of homogeneous rays through the earth's atmosphere, but first let us consider the basis of the formula.

We have seen that Bouguer's formula rests on the fundamental assumption that the light is not changed in its nature in passing from one layer to another, so that equal layers take out equal fractions. This is not the case except for homogeneous rays. It is therefore necessary to divide the beam up into parts, each containing rays of approximately homogeneous transmissibility. For this purpose it is necessary to observe the spectrum of the sunlight by the aid of the bolometer or other satisfactory delicate heat-measuring instrument. Even so, it is not possible to observe the transmission of the atmosphere at every wave-length, so as to determine the coefficients of transmission in the fine lines of absorption by water vapor and oxygen which are introduced by the earth's atmosphere. These lines are mainly grouped in the great bands made up of these fine lines which occur in the red and infra-red spectrum, and for them a special procedure must be adopted as was introduced by Langley. In general, however, the bolometer suffices to give us atmospheric transmission coefficients in sufficient number to deal with the gradually changing transparency of the air for rays of nearly adjacent wave-lengths. The proof of the formula for atmospheric transmission for homogeneous rays follows: It will be seen that the formula is one of extrapolation solely, and is not applicable to computations of the transparency at different barometric pressures, unless it be the fact (which is not usual) that the quality of the air from the different stations to the limit of the atmosphere is approximately identical. This indeed may be the case at very high elevations of 4,000 meters and over, but is not the case for ordinary observing stations, so that in the use of the formula of transmission it is generally erroneous to introduce the barometric pressure in the exponent as was done by Pouillet.

PROOF OF FORMULA FOR TRANSMISSION

Imagine the atmosphere to be made up of n concentric layers so chosen in thickness as to produce separately equal barometric pressures, and let the number n be so great that the transparency of any single layer is sensibly uniform, although the layers may differ from each other in trans-

parency by any gradual progression. The index of refraction of air is so near unity that there will be no sensible regular reflection in passing from one layer to the next, and the transmission of each layer may be expressed exponentially by Bouguer's formula, but with different coefficients of transmission for the several layers.

Thus, suppose E_0 to be the original intensity of a beam of light incident upon the outermost layer at the angle whose secant is m.

Then after passing successive layers the remaining intensities become

$$E_1 = E_0 a_1^{m_1}, \quad E_2 = E_0 a_1^{m_1} \cdot a_2^{m_2},$$
$$E_n = E_0 a_1^{m_1} a_2^{m_2} \ldots a_n^{m_n}. \quad (1)$$

The value of the secant of the angle of incidence will change slightly in passing from layer to layer from two causes: first, the curvature of the earth; second, the refraction of the beam in air. These causes produce opposite effects, the first tending to increase the angle of incidence, the second tending to diminish it as the beam approaches the earth's surface. Their combined effect is dependent on the height to which the temperature exercises absorption and on the distribution of density with the height. But it is generally supposed that the absorption of the air above 40 miles from the earth's surface is negligible, and, remembering that the atmospheric density diminishes with the height, it appears that for zenith distances less than 70° the effect of change of the secant of the angle of the incident beam from the outermost to the innermost layer of the atmosphere will not introduce error greater than 1 per cent. Accordingly for zenith distances less than 70° we may write approximately

$$E_n = E_0 (a_1 a_2 \ldots a_n)^m. \quad (2)$$

The symbols $a_1, a_2 \ldots a_n$ denote constants (providing no change of transparency occurs during the interval of time in question), and their values are slightly less than unity. We may substitute for their product a single constant, a, itself a proper fraction, and remembering that E_n is the intensity at the earth's surface, above denoted simply by E, we have

$$E = E_0 a^m. \quad (3)$$

LIMITATIONS OF FORMULA

No mention is made in this expression of the barometric pressure, but it is easy to see that an alteration of barometric pressure would signify, under the conventions adopted in deriving the formula, a change in the number of layers, n. This would cause an alteration of the quantity a, which is the continued product of the transmission coefficients of the layers, by introducing additional multipliers $a_{n+1}, a_{n+} \ldots$ or by the withdrawal of some $a_{n-1}, a_{n-1} \ldots$ Since we have no means of determining the value of the terms so introduced or taken away, there is no means of correcting for change of barometer in the use of the expression (3) and it would, for instance, be impossible to compute, from knowledge of the values of E, E_0, a and m for one station, what would be the value of E at some station of different barometric pressure.

From this we see that the unit of air mass to be taken for each station is the air mass traversed by beams from zenith celestial objects *between the station itself and the outer limit of the atmosphere,* and that the barometric pressure can not be employed in the computation to reduce observations at different stations to a common unit of air mass.

The determination of the solar constant of radiation, based upon the demonstration which has just been given, depends upon the following assumptions:

1. In a homogeneous medium, a homogeneous ray loses a fixed proportion of its intensity in every equal length of its path.

2. The earth's atmosphere may be considered as made up of a great number of layers concentric with the earth, each approximately homogeneous in itself over the area swept through by the solar beam between zenith distances of 70° and 30° during the time required for this sweep of the beam.

3. Surface reflection of the outer boundary of the atmosphere, or the boundaries of its internal layers, is negligible.

4. Except in the known red and infrared atmospheric bands, the transparency varies gradually from wave-length to wave-length, or if atmospheric absorption lines exist, the energy they absorb is inconsiderable.

5. Atmospheric bands do not exist in the solar spectrum outside the atmosphere.

6. The quantity of solar energy beyond $\lambda = 0.3\,\mu$ in the ultra-violet and beyond $\lambda = 3.0\,\mu$ in the infra-red is inconsiderable.

The soundness of these assumptions is best proved by the results of a great number of observations made at sea level and at high altitudes during the last ten years by different observers, but mainly by the staff of the Astrophysical Observatory of the Smithsonian Institution.

DISCUSSION OF LANGLEY'S SOLAR CONSTANT VALUE

With this preliminary we may perceive why the high solar constant value of Langley ought not to be accepted. For this purpose consider lines 26 to 43 of page 144 of the Mount Whitney report, which detail the precise method employed in obtaining what Langley regarded as a minimum value, namely 2.63 calories per square centimeter per minute.

We now proceed to determine from our bolometer observations a value which we may believe from considerations analogous to those just presented, to be a *minimum* of the solar constant, and one within the probable truth. All the evidence we possess shows, as we have already stated, that the atmosphere grows more transmissible as we ascend, or that for equal weights of air the transmissibility increases (and probably continuously), as we go up higher. In finding our minimum value we proceed as follows, still dealing with rays which are as approximately homogeneous as we can experimentally obtain them. Let us take one of these rays as an example, and let it be one whose wave-length is $0.6\,\mu$ and which caused a deflection at Lone Pine of 201. The coefficient of transmission for this ray as determined by high and low sun at Lone Pine and referred to the vertical air mass between Lone Pine and Mountain Camp is 0.976. From the observations at Lone Pine then, the heat of this ray upon the mountain should have been

$$201 \times 1{,}000 \div 976 = 206.0,$$

but the heat in this ray actually observed on the mountain was 249.7, therefore multiplying the value for the energy of this ray outside the atmosphere, calculated from Mountain Camp high and low sun observations (275) by the ratio 2497/2060 we have 333.3, where 333.3 represents the energy in this ray outside the atmosphere as determined by this second process. In like manner we proceed to deal with the rays already used, thus forming column 8 in Table 120.

It is evident that the transmission coefficient determined for the wave-length $0.6\,\mu$ by the aid of high and low sun observations at Lone Pine, represented the mean transmission of a ray of this wave-length through a mass of air containing all the kinds of strata between Lone Pine and the limit of the atmosphere. Such a transmission coefficient would certainly be greater than that which would have been found if the air had all been like that between Lone Pine and Mountain Camp, because the lower layers are least transparent,[3] therefore the value 0.976 could be known, *a priori, not* to represent the transmission of the air between Lone Pine and Mountain Camp, but to be certainly greater than the true transmission coefficient for the air between these stations. Accordingly the discrepancy between the computed and observed intensities at Mountain Camp is only what should be expected, and implies no failure of the formula of Bouguer at all; for that formula was used in the computation of the intensity at Mountain Camp just quoted with a coefficient p which was certainly wrong. The argument on which Langley acted may be stated in a plausible form as follows: If Bouguer's exponential formula with the transmission coefficient obtained by high and low sun observations at Lone Pine gives too low a value of the intensity of homogeneous solar radiation for a station within the atmosphere like Mountain Camp, as was shown by actual observation, much more will it

[3] See Table 118 of the Mount Whitney Report.

give too low a value outside the atmosphere. An equally plausible, and equally fallacious argument is the following: It is said that the density of water decreases with increasing temperature at the mean rate of about .00041 per degree from 0° to 100°. Hence its density at 4° should be 0.99836, but observations at 4° prove that water is actually denser at this temperature than at 0°, therefore the supposed decreased density at 100° is a delusion.

SOLAR CONSTANT WORK OF THE SMITHSONIAN ASTROPHYSICAL OBSERVATORY

The earlier years of the work of the Astrophysical Observatory were devoted to the improvement of the bolometer and the use of it for the determination of the positions of lines in the infra-red solar spectrum. About 1902 attention began to be devoted to measurements of the solar constant of radiation. We approached these measurements with a very much better instrumental equipment than that which had been Langley's in the Mount Whitney expedition of 1881. Soon after the Astrophysical Observatory was founded, about the year 1890, Langley introduced the automatic registration of the galvanometer in connection with the spectro-bolometer, and in the subsequent years the difficulties connected with the use of the recording spectro-bolometer were so far overcome that the solar spectrum could be observed from the extreme ultra-violet end of the spectrum at about 0.3 μ to a wave-length of about 3 μ in the infra-red with great ease and accuracy, in an interval of 8 minutes of time. Drift of the galvanometer, which in Langley's expedition to Mount Whitney he has told me often amounted to a meter a minute on the scale, was now so far reduced that a centimeter an hour would be unusual. In fact the bolometer, despite its great sensitiveness, is about as easy to use for this work as an ordinary thermometer is for measuring the temperature of the air.

Our first measurements of the sun's radiation as a whole were made with the Crova alcohol actinometer, and in order to standardize this instrument we constructed a modified Tyndall pyrheliometer consisting of a copper box filled with mercury and having a cylindric bulb thermometer inserted radially into the box. Owing to the difficulty of keeping the small thread of mercury at the proper point for reading purposes in the Crova actinometer, we found it more desirable to develop the pyrheliometer for our purpose. Soon a solid disk of copper with a radial hole large enough to enclose the thermometer bulb was substituted for the box filled with mercury, the use of mercury being limited to insuring a good heat connection between the bulb of the thermometer and the copper of the disk. Some of these copper disk pyrheliometers are still in use on Mount Wilson. About 1909, however, the further improvement was introduced of using silver in place of copper for the disk. A thin steel lining is provided for the hole where the thermometer is inserted, so as to prevent the mercury from alloying with the silver. In these silver disk instruments the thermometer stem, which is introduced radially in the disk, is bent outside the chamber at right angles so as to point towards the sun. The whole instrument is mounted equatorially with a device for moving it by hand to follow the sun from moment to moment. These disk pyrheliometers, either of copper or silver, have now been in use since the year 1906 with great satisfaction. Their constancy over long periods of time leaves nothing to be desired, and the accuracy of observation reaches a small fraction of 1 per cent.

As the disk pyrheliometer is a secondary instrument, it was necessary to develop a

standard primary instrument to compare it with. As early as the year 1904 experiments were begun to produce a pyrheliometer based upon the hollow chamber "black body" type, with a flowing liquid to carry off the heat produced by the absorption of the solar rays within such a chamber. After numerous experiments and long trial the waterflow standard pyrheliometer was fully developed in the year 1910. Later still, another hollow chamber instrument in which the chamber is bathed with stirred water was employed to check the results of the standard water-flow instruments. In each of these types of standard instruments it is possible to introduce electrically known quantities of heat for testing purposes, and in many experiments it has been proved that the test quantities of heat thus introduced may be recovered to within 1 per cent. Accordingly it is believed that the standard scale of radiation has been thoroughly established. The silver disk instruments are standardized by comparing them with such standard instruments, and the standard scale of radiation so produced, which is believed to be accurate to at least ½ of 1 per cent., has been diffused generally over the world by the Smithsonian Institution. About 25 copies of the silver-disk pyrheliometer have been standardized and sent out to Europe, North America and South America for this purpose. The Smithsonian instruments read about 3.5 per cent. above those of Ångström.

Measurements of the solar constant of radiation were begun in Washington in the year 1902 and have been continued at Washington and elsewhere in every succeeding year until the present time. In 1903 it was noticed that the values of the solar radiation outside the atmosphere obtained in Washington were distinctly variable within the limits of about 10 per cent., and as some of the changes appeared to occur between days which were of the highest order of excellence, it was thought possible that these changes might occur in the sun, and not be caused by alterations of the transparency of the earth's atmosphere. To test this possibility, a station was established on Mount Wilson, California, in the year 1905 by invitation of Director Hale of the Mount Wilson Solar Observatory. The station proved to be very favorable for the work, and in 1908 a permanent structure of cement was built there for the use of the Smithsonian Astrophysical Observatory. In the years 1909 and 1910 spectro-bolometric observations for the determination of the solar constant of radiation were also made on the extreme summit of Mount Whitney in California at an altitude of 4,420 meters. At the same time observations were being made at Mount Wilson at an altitude of 1,730 meters. The results from these two stations reduced to outside the atmosphere at mean solar distance, like those which had formerly been obtained simultaneously at Washington and Mount Wilson, were identical within the limit of the accuracy of the determinations. The accuracy of the work at Mount Wilson and Mount Whitney was so great that the average divergence between the observations of the same days was only 1 per cent. At Washington the sky conditions being less perfect, the average divergence from simultaneous solar-constant results of Mount Wilson was about 3 per cent.

EVIDENCES OF SOLAR VARIABILITY OF SHORT IRREGULAR PERIODS

Numerous observations of several years at Mount Wilson indicated a fluctuation in the solar constant values having a range of about 10 per cent. The fluctuations seemed to occur irregularly, sometimes running their course of 10 per cent. or less

within the period of a week or ten days, and at other times keeping nearly constant. It had been shown by the observations made simultaneously at Mount Wilson and at Mount Whitney that the results as reduced outside the atmosphere appear to be independent of the altitude of the observing station on days when the sky conditions appeared to the eye to be excellent. The march of the apparent fluctuation of the solar constant values at Mount Wilson has not been of a hap-hazard character. I mean by this that the values would progress in a definite direction, as for instance from a low value to a high value by steps through several successive days, and then as definitely progress in the opposite direction through other successive days, and do not fluctuate widely from high values to low as would be the case if the irregularities were due merely to instrumental error. Since, then, it appeared that the fluctuations were neither of an accidental instrumental character nor of a character associated with the altitude of the observing station, it appeared most reasonable to conclude that these fluctuations were due to changes in the sun's emission.

To test this important conclusion it appeared necessary to establish a second station, equally favorably situated with regard to sky conditions as Mount Wilson, but so far remote from Mount Wilson that local influences could not be expected to alter the results at both stations in the same direction on the same day. Such a station was established at Bassour, Algeria, in the years 1911 and 1912. Seventy-five days of simultaneous measurement at Mount Wilson and at Bassour were obtained, and of these days about 50 were so far free from the occurrence of clouds or other disturbing influences at *both* stations as to be retained for purposes of comparison. The result of the comparison shows that when high values are obtained at Bassour, high values are obtained also at Mount Wilson and *vice versa*. Thus the fluctuations which have been found appear to be truly existing in the solar radiation outside the earth's atmosphere, for the solar constant values obtained at two stations separated by about one third the circumference of the earth unite in showing them.

VALUE OF THE SOLAR CONSTANT

During the whole solar constant campaign from 1902 to 1913, about 700 measurements of the solar constant of radiation have been obtained, all but three of the values ranging between 1.80 calories and 2.10 calories. The range of these numbers is mainly attributable to the actual fluctuation of the sun itself, though part, especially in Washington work, is due to accidental errors of measurement. The mean value from 690 measurements is 1.933 calories per square centimeter per minute. It is believed that this number represents the average value of the solar constant of radiation for the epoch 1902 to 1913 within 1 per cent. There is still the possibility, however, that an appreciable quantity of solar radiation beyond the wave-length of $0.3\,\mu$ in the ultra-violet has been absorbed by ozone in the higher atmosphere of the earth, and has been impossible of determination at the stations employed. However, from the consideration of the form of energy curve of the sun's spectrum it is improbable that this lost ultra-violet radiation can exceed 1 or 2 per cent.

SOLAR VARIABILITY ASSOCIATED WITH SUN-SPOTS

Besides the short irregular fluctuation of solar radiation above mentioned as having been shown by the simultaneous measurements at Mount Wilson and Bassour,

Algeria, it appears that a long period fluctuation is associated with the sun-spot numbers. This connection is brought out by taking the mean monthly values of the solar constant measurements at Mount Wilson from the year 1906 on, and comparing them with the mean monthly sun-spot numbers of Wolfer for the same period. From such a comparison it appears that the greater number of sun-spots the higher will be the solar constant of radiation, and that an increase of a hundred sun-spot numbers corresponds to an increase of about 0.07 calories per square centimeter per minute in the solar radiation outside the earth's atmosphere. This is a very curious circumstance, when it is recalled that the temperature of the earth is generally lower at sun-spot maximum than at sun-spot minimum, notwithstanding that, if the above result be true, the solar radiation is more intense at sun-spot maximum than at sun-spot minimum. On the other hand, the result is in line with the irregular variability of the Myra type of variable stars.

ATMOSPHERIC TRANSMISSION

In connection with the measurements which have been made of the solar constant of radiation, there have been some interesting by-products. Among these we may mention first the determination of the transmission coefficients of the earth's atmosphere for light of all wave-lengths, including the ultra-violet and the infra-red spectrum, and ranging from wave-length $0.3\,\mu$ in the ultra-violet to wave-length $2.5\,\mu$ in the infra-red. These transmission coefficients have been obtained by the Smithsonian observers at Washington, Mount Wilson, Mount Whitney and Bassour. It is very interesting to compare them with the transmission of the atmosphere as computed according to the theoretical consideration of Rayleigh on the cause of the light of the sky. It is found that by means of these observed transmission coefficients the value of the number of molecules in the atmosphere may be obtained almost as accurately as by the use of the more common laboratory methods for determining the number of molecules per cubic centimeter of a gas of known density. It is found that the theory of Rayleigh connecting the change of transmission with the wave-length is closely confirmed by the observations at Bassour, Mount Wilson and Mount Whitney. Similar measurements of atmospheric transmission for more limited regions of the spectrum have been made by other observers at high altitudes, and these also are found to agree closely with the theory of Rayleigh, and with our own observations.

Not less interesting is the determination of the distribution of energy in the sun's spectrum, and thereby of the probable temperature existing in the sun. The solar temperatures may be inferred also from the value of the solar constant of radiation itself, and the two methods agree substantially in giving the probable solar temperatures as between 6,000 and 7,000 degrees absolute centigrade.

RECENT BALLOON EXPERIMENTS

Notwithstanding the satisfactory state of the theory of solar constant measurements by the method of Langley, depending upon spectro-bolometric observations at high and low sun combined with measurements by the pyrheliometer, and notwithstanding the close agreement between results obtained by this method for many years at stations of differing altitude from sea-level to 4,420 meters elevation, there still exists the possibility that if we could, indeed, go outside the atmosphere altogether we should obtain values differing materially from those above given. So

long as we observe at the earth's surface, no matter how high the mountain top on which we stand, the atmosphere remains above us, and some estimate must be made of its transmission before the solar constant can be determined. Different persons will differ in the degree of confidence which they will ascribe to measurements of the atmospheric transmission, such as have been considered, and there are still some who totally disbelieve in the accuracy of the results thus far obtained, even though they be confirmed by observations at such differing altitudes. Accordingly it has seemed highly desirable to check the results by a method of direct observation by the pyrheliometer, attaching the instrument for this purpose to a balloon and sending it to the very highest possible altitudes. By a cooperation between the Smithsonian Institution and the United States Weather Bureau, experiments for this purpose were made in July and August of the year 1913.

The instruments employed were modified in form from the silver-disk pyrheliometer, which has been described above. As the apparatus could not be pointed at the sun the disk was placed horizontally, and the thermometer was contrived to record its temperature by photography upon a moving drum. The receiving disk was alternately exposed to the sun and shaded by the intervention of a shutter, operated intermittently by the clock work which rotated the drum under the stem of the thermometer. Five instruments of this kind were sent up on successive days. While it was well known that the temperature of the higher air would go as low as —55° C., it was believed that a blackened disk exposed half the time to the direct sun rays, would certainly remain above the temperature of —40°, which is the freezing point of mercury. This expectation was disappointed. Accordingly, owing to the freezing of the mercury in the thermometer, the highest solar radiation records obtained during the expedition were at the altitude of 13,000 meters, although the balloons in some instances reached the altitude of 33,000 meters.

The results obtained, while they have not the same degree of accuracy as those obtained by direct reading of the silver disk pyrheliometer, are yet of considerable weight. All the measurements unite in indicating values of the solar radiation at altitudes of 10,000 meters and higher, which fall below the value of the solar constant of radiation as obtained by other methods, and above the value of the radiation at the summit of Mount Whitney as obtained by different observers with pyrheliometers. It is expected in the coming year to repeat the observations with balloons under much improved circumstances. By aid of electrical heating apparatus it is expected to keep the surroundings of the disks at approximately the freezing temperature, even though exposed to the air at temperatures as low as —55° C. In this way it is hoped to obtain good pyrheliometer measurements as high as it is possible for sounding balloons to go, and possibly to an altitude of 40,000 meters. As the atmospheric pressure at such altitudes is less than 1 per cent. of that prevailing at sea level, the experiments, if successful, may be expected to remove reasonable doubt of the value of the solar constant of radiation.

C. G. Abbot

SETH CARLO CHANDLER

Dr. Seth Carlo Chandler, eminent astronomer, died on December 31, 1913, in his sixty-seventh year after a short attack of pneumonia.

Born at Boston, Mass., September 17, 1846,